Density Dependence of Nucleon Bag Constant, Radius and Mass in an Effective Field Theory Model of QCD[1]

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Abstract

With the global color symmetry model (GCM) being extended to finite chemical potential, the density dependence of the bag constant, the total energy and the radius of a nucleon, as well as the quark condensate in nuclear matter are investigated. A maximal nuclear matter density for the existence of the bag with three quarks confined within is obtained. The calculated results indicate that, before the maximal density is reached, the bag constant, the total energy of a nucleon and the quark condensate decrease gradually, and the radius of a nucleon increases, with the increasing of the nuclear matter density. Nevertheless no sudden change emerges. As the maximal nuclear matter density is reached, a phase transition from nucleons to quarks takes place and the chiral symmetry is restored.

1 Introduction

It is well known that the nucleonic and mesonic degrees of freedom play essential roles in describing properties of nuclear matter and finite nuclei. Meanwhile, nucleons bound in nuclear medium alter their properties from those in free space. Although how much those properties change is of fundamental interest in nuclear physics, it is still not clear now. Then, in the relativistic mean field theory (RMF) based on the $\sigma - \omega$ model, which is currently regarded as a standard model of nuclear physics, the effective nucleon mass in nuclear medium is determined in self-consistent iteration on the fields of nucleons and mesons (see, for example, Ref.[1]). However, this model is valid only at the hadronic level, at which a nucleon is described as a point-like particle. Because of the importance of the substructure of nucleon observed in deep inelastic scattering experiments and predicted by quantum chromodynamics (QCD), it is imperative to employ the quark and gluon degrees of freedom to describe nuclear phenomena. Unfortunately, it is now very difficult to make quantitative predictions with QCD at low and intermediate energy region. Therefore various phenomenological models based on the QCD assumptions, such as the bag models[2, 3], quark-meson coupling (QMC) model[4], and so on, have been developed. In bag models, the fundamental quantities to characterize a nucleon is the bag constant, the radius and the energy of the bag. In the QMC model, nucleons are regarded as non-overlapping bags interacting through the exchange of mesons. The size and mass of a nucleon are represented by the radius and energy of the bag, respectively, too. In order to take the modification of the volume energy on the mass of a nucleon into account, the bag constant is also exploited in the QMC model. Originally, the bag constant held fixed as its free-space value in bag models[4], then a density dependent bag constant is introduced by a phenomenological dependence on the medium density[5, 6, 7, 8, 9]. However, a sophisticated QCD foundation of the density dependence of the bag constant, the radius and the mass of a nucleon is still lacking.

Recently, an effective field theory of QCD, namely the global color symmetry model (GCM), has been developed[10, 11, 12, 13], and shown to be quite successful in describing hadron properties in free space(i.e., at temperature $T = 0$, chemical potential $\mu = 0$). With the Dyson-Schwinger equation approach of QCD being extended to finite temperature, the deconfinement and chiral symmetry restoration, the π and ρ meson properties, and a part of the baryon properties at finite-T and finite-μ have been investigated [14, 15, 16, 17, 18, 19]. With the nontopological-soliton ansatz[3], some parameters related to the nucleon structure, such as the bag constant, had also been introduced in the GCM at $T = 0$ and $\mu = 0$ in a natural way[10]. It seems that a QCD foundation for the bag models is proposed at the level of the GCM model. With the global color symmetry model

being extended to finite chemical potential μ, the dependence of the nucleon properties, such as the bag constant, the total energy and the radius of a nucleon on the nuclear medium density will be studied in this paper.

The paper is organized as follows. In Section 2 we describe the formalism of the GCM model at finite chemical potential μ and the model of the relation between the chemical potential of quarks and the baryon density in nuclear matter. In Section 3 we represent the calculation and the obtained results of the bag constant, the bag radius and the bag energy, as well as the quark condensate as functions of the nuclear matter density. It contains also discussions on the results. In Section 4, a brief summary and some remarks are given.

2 Formalism

It has been known that the action of the GCM in free space (i.e., at chemical potential $\mu = 0$) for the zero mass quark is given[10] in the Euclidean space as

$$S = \int d^4x d^4y \overline{q}(x) \left[\gamma \cdot \partial \delta(x - y) + \Lambda^\theta B^\theta(x, y) \right] q(y) + \int d^4x d^4y \frac{B^\theta(x, y) B^\theta(y, x)}{2g^2 D(x - y)} ,$$

where $B^\theta(x, y)$ is a bilocal field and Λ^θ are matrices of the Fierz transformation among the spin, color, and flavor spaces of the quarks. Extending it to finite chemical potential μ, we have the action of the GCM at finite chemical potential as

$$S = \int d^4x d^4y \overline{q}(x) \left[\gamma \cdot \partial \delta(x - y) - \mu \gamma_4 + \Lambda^\theta B^\theta(x, y) \right] q(y) + \int d^4x d^4y \frac{B^\theta(x, y) B^\theta(y, x)}{2g^2 D(x - y)} ,$$

from which the generating functional is defined as

$$Z[\overline{\eta}, \eta] = \int D\overline{q} Dq DB^\theta e^{[-S + \overline{\eta}q + \overline{q}\eta]} .$$

After integrating the quark fields, we obtain

$$S = -\text{Trlog} \left[\gamma \cdot \partial \delta(x - y) - \mu \gamma_4 + \Lambda^\theta B^\theta \right] + \int d^4x d^4y \frac{B^\theta(x, y) B^\theta(y, x)}{2g^2 D(x - y)} . \tag{1}$$

Generally, the bilocal field $B^\theta(x, y)$ can be written as[13]

$$B^\theta(x, y) = B_0^\theta(x, y) + \sum_i \frac{B_0^\theta(x, y)}{f_i} \phi_i^\theta(\frac{x + y}{2}) , \tag{2}$$

where $B_0^\theta(x, y) = B_0^\theta(x - y)$ is the vacuum configuration of the bilocal field. In the lowest order approximation with only the Goldstone boson being taken into account, the ϕ_i^θ

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includes σ and π mesons, and f_i $(i = \sigma, \pi)$ stands for the decay constant of σ, π mesons, respectively. The vacuum configuration can be determined by the saddle-point condition $\frac{\partial S}{\partial B_0^\theta} = 0$, and a equation of the translation invariant quark self-energy $\Sigma(q, \mu)$ is obtained as

$$\Sigma(p, \mu) = \int \frac{d^4p}{(2\pi)^4} g^2 D(p - q) \frac{t^a}{2} \gamma_\nu \frac{1}{i\gamma \cdot q - \mu\gamma_4 + \Sigma(q, \mu)} \gamma_\nu \frac{t^a}{2} . \qquad (3)$$

With $\tilde{q}_\mu = (\vec{q}, (q_4 + i\mu))$ being introduced, Eq. (3) can be rewritten as

$$\Sigma(p, \mu) = \int \frac{d^4q}{(2\pi)^4} g^2 D(x - y) \frac{t^a}{2} \gamma_\nu \frac{1}{i\gamma \cdot \tilde{q} + \Sigma(q, \mu)} \gamma_\nu \frac{t^a}{2} .$$

Taking the conventional decomposition for the quark self-energy

$$\Sigma(p, \mu) = i[A(\tilde{p}) - 1]\gamma \cdot \tilde{p} + V B(\tilde{p}) , \qquad (4)$$

where $V = \sigma + i\vec{\pi} \cdot \vec{\tau}\gamma_5$ with restriction $\sigma^2 + \vec{\pi}^2 = 1$, one can fix the self-energy $\Sigma(p, \mu)$ by solving the rainbow Dyson-Schwinger equations

$$[A(\tilde{p}) - 1]\tilde{p}^2 = \frac{8}{3} \int \frac{d^4q}{(2\pi)^4} g^2 D(p - q) \frac{A(\tilde{q})\tilde{q} \cdot \tilde{p}}{A^2(\tilde{q})\tilde{q}^2 + B^2(\tilde{q})} , \qquad (5)$$

$$B(\tilde{p}) = \frac{16}{3} \int \frac{d^4q}{(2\pi)^4} g^2 D(p - q) \frac{B(\tilde{q})}{A^2(\tilde{q})\tilde{q}^2 + B^2(\tilde{q})} . \qquad (6)$$

Basing on the solution of the Dyson-Schwinger equations, one can determine the bilocal field, and fix further the GCM action.

With a nontopological-soliton ansatz, the action of the bag models at finite chemical potential μ in terms of the GCM can be given by extending the formalism proposed in Ref.[10] as

$$S_B = \sum_{i=1}^{3} \overline{q}_i[i\gamma \cdot \partial + \mu\gamma_0 - \alpha(\sigma(x) - i\vec{\pi}(x) \cdot \vec{\tau}\gamma_5)]q_i + \hat{S}(\sigma, \pi, \mu) , \qquad (7)$$

where $\hat{S}(\sigma, \pi, \mu)$ includes only σ and π mesons and reads

$$\hat{S}(\sigma, \pi, \mu) = \int [\frac{f_\sigma^2}{2}(\partial_\mu\sigma)^2 + \frac{f_\pi^2}{2}(\partial_\mu\vec{\pi})^2 - V(\sigma, \pi)]d^4z + \cdots \qquad (8)$$

with

$$V(\sigma, \pi) = -\frac{12\pi^2}{(2\pi)^4} \int_0^\infty s'ds' \left\{ \log \left[\frac{A^2(s')s' + (\sigma^2 + \vec{\pi}^2)B^2(s')}{A^2(s')s' + B^2(s')} \right] - \frac{(\sigma^2 + \vec{\pi}^2 - 1)B^2(s')}{A^2(s')s' + B^2(s')} \right\} .$$

Analyzing the stationary property of the bag and differentiating Eq. (7), one has equations for the quarks and mesons

$$[i\gamma \cdot \partial + \mu\gamma_0 - \alpha(\sigma(x) - i\vec{\pi}(x) \cdot \vec{\tau}\gamma_5)] q_i = 0 , \qquad (9)$$

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$$\frac{\partial S_B}{\partial \sigma(x)} = 0 \tag{10}$$

$$\frac{\partial S_B}{\partial \pi(x)} = 0 \,. \tag{11}$$

The quark field and σ, π meson fields in symmetric nuclear matter can be determined by solving the Eqs. (9-11) self-consistently. As a consequence, the corresponding energies can be obtained. From the restriction on the quark self-energy (Eq. (4)), it is apparent that the meson fields corresponding to the vacuum configuration can be simply taken as $\sigma = 1$, $\pi = 0$ under mean-field approximation. In light of the nontopological-soliton ansatz[3, 10], one can take the meson fields as $\sigma = 0$ and $\pi = 0$ inside a bag (i.e., in a nucleon). For the quarks in a bag, Eq. (9) can thus be rewritten in the mean-field approximation as

$$[i\gamma \cdot \partial + \mu\gamma_0]\, q_i(x) = 0 \tag{12}$$

The lowest total energy of a single quark with respect to the radius R of the bag is given as

$$\epsilon_i(R) = \frac{\omega_0}{R}, \tag{13}$$

where $\omega_0 = 2.04$. This is consistent with the results obtained in Refs[2, 5, 6]. And the bag constant $\mathcal{B}$ is obtained as

$$\mathcal{B} = \frac{12\pi^2}{(2\pi)^4} \int_{\mu^2}^{\infty} s'ds' \left\{ \log\left[\frac{A^2(s')s' + B^2(s')}{A^2(s')s'} \right] - \frac{B^2(s')}{A^2(s')s' + B^2(s')} \right\}, \tag{14}$$

with $s' = \tilde{p}^2$. With the correction from the motion of center-of-mass, the zero-point effect and the color-electronic and color-magnetic interactions being taken into account, the total energy of a bag is given as

$$E = 3\epsilon(R) + \frac{4}{3}\pi R^3 \mathcal{B} - \frac{Z_0}{R} = \frac{3\omega_0 - Z_0}{R} + \frac{4}{3}\pi R^3 \mathcal{B}, \tag{15}$$

where Z_0/R denotes the corrections of the motion of center-of-mass, zero-point energy and other effects.

Just as the same as that in Ref.[10], the bag is identified as a nucleon in the present work. It satisfies then the equilibrium condition

$$\frac{dE(R)}{dR} = 0 \,.$$

From this condition, we get

$$R = \left(\frac{a}{4\pi\mathcal{B}} \right)^{1/4} \tag{16}$$

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where $a = 3\omega_0 - Z_0$. As a consequence, Eq. (15) can be rewritten as

$$E = \frac{4a}{3}\left(\frac{4\pi\mathcal{B}}{a}\right)^{1/4}. \tag{17}$$

It is apparent that, with the solutions of Dyson-Schwinger equations (Eqs. (5) and (6)) being taken as the input for Eqs. (14), (16) and (17), the properties of nucleons (i.e., bags) in nuclear matter can be obtained. Because the quark condensate has commonly been taken as the order parameter to characterize the phase transition for chiral symmetry restoration [20, 21], we evaluate also the variation of the quark condensate against the density of nuclear matter

$$< \overline{q}q > = <: \overline{q}(0)q(0) :> = TrS(x,x) = -\frac{12}{(2\pi)^4}\int_{\mu^2}^{\infty} s'ds'\frac{B(s')}{A^2(s')s' + B^2(s')}. \tag{18}$$

In the practical calculation, since the knowledge about the exact behavior of g^2 and $D(p-q)$ in low energy region is still lacking, one has to take some approximations or phenomenological form to solve the Dyson-Schwinger equations. For simplicity, we adopt the infrared dominative form[22, 10]

$$g^2 D(p-q) = \frac{3}{16}\eta^2\delta(p-q), \tag{19}$$

where η is a energy-scale parameter and can be fixed by experiment data of mesons. Although this form does not include the contribution from the ultraviolet energy region, it maintains the main property of QCD in the low energy region. With Eqs. (5), (6) and (19), one has

$$A(\tilde{p}) = 2, \qquad\qquad B(\tilde{p}) = (\eta^2 - 4\tilde{p}^2)^{1/2}, \qquad \text{for} \quad \tilde{p}^2 < \frac{\eta^2}{4}, \tag{20a}$$

$$A(\tilde{p}) = \frac{1}{2}\left[1 + \left(1 + \frac{2\eta^2}{\tilde{p}^2}\right)^{1/2}\right], \quad B(\tilde{p}) = 0, \qquad\qquad \text{for} \quad \tilde{p}^2 > \frac{\eta^2}{4}. \tag{20b}$$

In order to investigate the dependence of nucleon properties on the nuclear matter density ρ explicitly, we must transfer the above obtained μ-dependence to that of the ρ-dependence. Because of the fermionic properties of quarks, the bags can be approximately regarded as a Fermi-Dirac systems[23] with the fermion number density

$$n = g\int_0^{k_F} \frac{d^3\vec{k}}{(2\pi)^3}, \tag{21}$$

where g is the degenerate factor, and k_F is the Fermi momentum. For the quarks in a nucleon, g is 12, and

$$k_F = (\mu^2 - m_q^2)^{1/2},$$

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where m_q is the current quark mass. In case of zero current quark mass, one has $k_F = \mu$. In the lowest order approximation, we get the quark number density as

$$n_q = \frac{2}{\pi^2}\mu^3 \,. \tag{22}$$

Considering the fact that the baryon number for a quark is $1/3$, one can take the relation between the nuclear matter density and the chemical potential as

$$\rho_B = \frac{n_q}{3} = \frac{2}{3\pi^2}\mu^3 \,. \tag{23}$$

Combining Eqs. (14), (16-18), (20) and (23), we can obtain the dependence of the bag constant $\mathcal{B}$, the total energy E and the radius R of a nucleon (i.e., those of a bag) and the quark condensate on the nuclear matter density ρ_B.

3   Calculation and Results

By calibrating the nucleon mass $M_0 = 939$ MeV as the total energy of a bag and radius $R_0 = 0.8$ fm in free space (i.e., $\mu = 0$, $\rho = 0$), we get the energy-scale $\eta = 1.220$ GeV, $Z_0 = 3.303$. Such best fitted energy-scale η fits well the value 1.37 GeV, which was fixed by a good description of π and ρ meson masses[16, 17], and is much more close to the Bjorken-scale 1.0 GeV (see Ref.[23] and the references therein). The obtained Z_0 is larger than the originally fitted value 1.84[24]. However what we refer to here includes all the effects but not only the zero-point energy. Meanwhile other investigations (see for example Ref.[25]) have shown that the zero-point energy parameter can be larger than 1.84, even though the other effects are taken into account separately. With the above parameters η, Z_0 and Eqs.(17) and (18), we get at first the bag constant, and the quark condensate in free space as $\mathcal{B}_0 = (172 \text{ MeV})^4$, and $< \bar{q}q >_0 = -(132 \text{ MeV})^3$. It is evident that these obtained values B_0 and $< \bar{q}q >_0$ are quite close to the results given in Ref.[6] and Ref.[20], respectively.

By varying the chemical potential μ, we obtain the relation between the nuclear matter density and the chemical potential of the quarks, which exhibits the same monotonousness apparently. Furthermore, we get the variation behavior of the ratio of bag constant, the nucleon radius, the total energy of the bag and the quark condensate in nuclear matter to the corresponding value in free space against the nuclear matter density. The results are illustrated in Figs. 1-4, respectively.

Looking over the figures, one may easily realize that, as the density of nuclear matter increases, the bag constant, the total energy of the bag and the quark condensate decrease monotonously. Meanwhile, the radius of a nucleon increases. When the nuclear matter
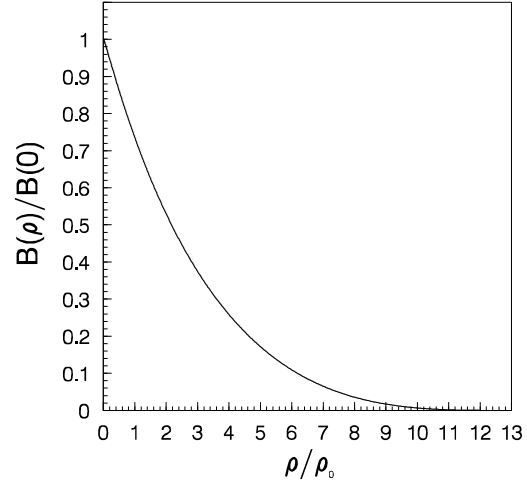
Figure 1: Calculated ratio between the bag constant in nuclear matter and that in free space as a function of the nuclear matter density
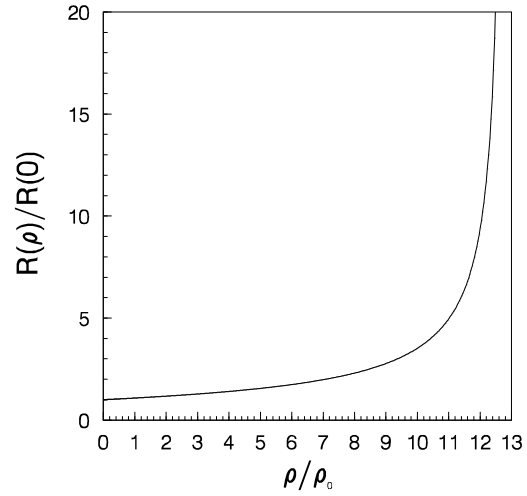

Figure 2: Calculated ratio between the radius of nucleon in nuclear matter and that in free space as a function of the nuclear matter density
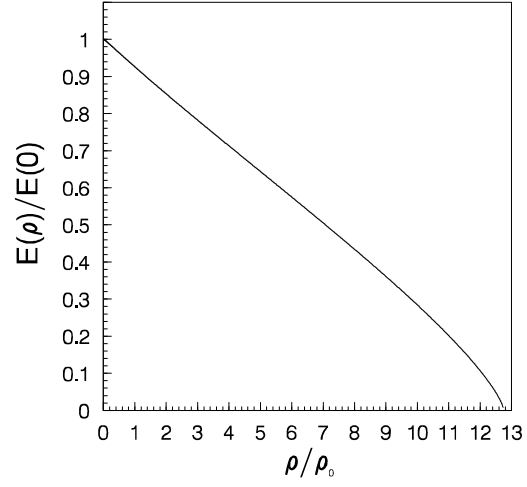
Figure 3: Calculated ratio between the total energy of a bag in nuclear matter and that in free space as a function of the nuclear matter density
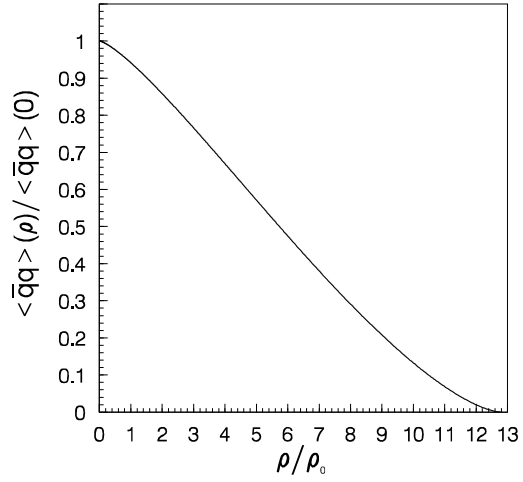

Figure 4: Calculated ratio between the local quark condensate in nuclear matter and that in free space as a function of the nuclear matter density

density reaches the value larger than 12 times the normal nuclear matter density (referred to as ρ_0), the bag constant, the total energy of a bag and the quark condensate vanish simultaneously, and the radius of a nucleon becomes infinite. Such behaviors indicate that nucleons can no longer exist as bags consisting of quarks. Since the density $12\rho_0$ is larger than the maximal average hadron density of neutron stars, which is commonly believed to be about $10\rho_0$, the presently obtained results show that the nuclear matter changes to quark matter, i.e., the phase transition from hadrons to quarks happens, as the density of nuclear matter gets beyond the maximal average density of neutron stars. It provides a clue that there may be quark matter or hybrid matter with hadrons and quarks in the center part of neutron stars. This is something similar to the result given in Ref.[26]. On the other hand, the quark condensate $< \overline{q}q >$ has been regarded to be a manifestation to identify the chiral symmetry breaking. The gradual decrease of the quark condensate indicates that the chiral symmetry is restored gradually as the nuclear matter density increases. When the nuclear matter becomes quark matter, the chiral symmetry is restored completely since the quark condensate vanishes. It indicates that the quark decoupling phase transition and the chiral phase transition may happen at the same nuclear matter density. It is also worth mentioning that the increase of the nucleon radius induces naturally the swell of nucleons, which is believed to be essential to the EMC effect (see for example Ref.[28]).

To show the function of the bag in nuclear matter and the process of the phase transition, we evaluate the critical radius of the bag in nuclear matter and the variation feature of the pressure of the bag against the nuclear matter density. In a classical point of view, the relation between the critical radius of the bag r_c and the nuclear matter density ρ reads

$$\rho \frac{4}{3} r_c^3 = 1\,.$$

From the thermodynamics of quark system[27], the pressure in a bag with quarks

$$p = \int_0^\mu n d\mu - \mathcal{B}\,.$$

The numerical results of the critical radius and the pressure of the bag are displayed in Figs.5 and 6, respectively. It is evident that, as the nuclear matter is dilute, the pressure of the bag is negative so that the bag exists definitely and three quarks are bound in a bag to form a nucleon. Furthermore, the bags exist separately from each other, since the radius of a bag is smaller than the critical radius r_c. When the density of nuclear matter increases, the bags get close to each other. As the nuclear matter density is about 2 times the normal density of nuclear matter, the nucleons begin to overlap with each other. However, every nucleon prefers to exist as an independent bag since the pressure
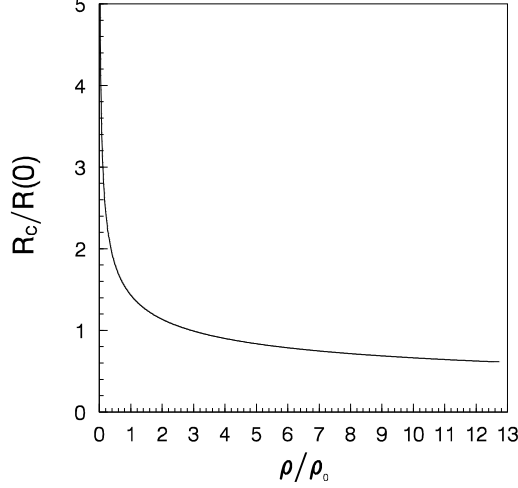
Figure 5: Calculated critical radius of a bag in nuclear matter with respect to the nuclear matter density

of the bag is still negative. As the density $\rho > 3\rho_0$, the pressure changes to positive. It is definite that such a positive pressure enhances the overlapping among nucleons. Then quark matter appears as all the nucleons overlap with each other completely as the nuclear matter density $\rho > 12\rho_0$. As a consequence, the phase transition from hadrons to quarks takes place. On the other hand, taking the same way as that in determining the relation between nuclear matter density and quark chemical potential, and considering the fact that the degeneracy of nucleons is $g = 4$, one can easily get that $\rho_B = \frac{2}{3\pi^2}\mu_B$. Comparing this result with Eq. (23), one can know that the chemical potential of quarks is just the same as that of nucleons. Such a equivalence means that the phase transition can happen.

Figures 1 and 2 show also that, before the phase transition takes place, the changing characteristics of the bag constant and the radius of a nucleon coincide with the results obtained in the QMC model with a phenomenological dependence on the scalar meson field being involved[5, 6, 7, 8]. Such a behavior indicates that, dealing the bag constant and the bag radius with a phenomenological dependence on the medium density in the QMC model is reasonable. Nevertheless, Fig. 3 shows that the change of the total energy of a bag is much less rapid than that of nucleon mass obtained in QMC and other frameworks. Tracking down the source of the discrepancy, one knows that the total energy of a bag is not identical to the mass of a nucleon, but with a relation $M = \sqrt{E^2 - <p>^2}$. Taking
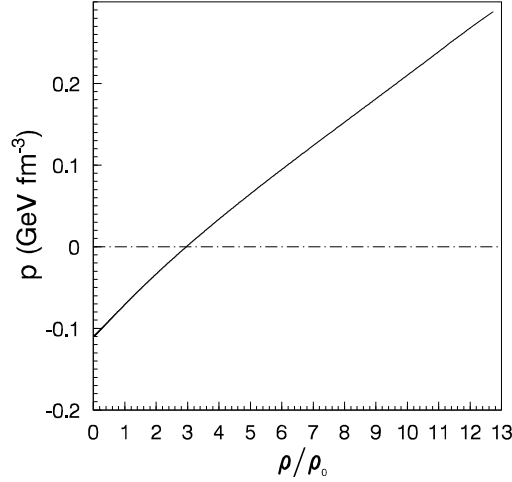
Figure 6: Calculated pressure of the bag with respect to the nuclear matter density

$< p >^2= \mu_B^2$ approximately, we get that, at the normal density of nuclear matter, the mass of a nucleon decreases to about 85% of the value in free space. This is consistent with the result determined self-consistently in the derivative scaler coupling model of the RMF[8]. It means then the effective mass of nucleons in RMF calculations is also reasonable. Such agreements show that present model can reproduce the quantities and their variation characteristics obtained in the QMC model and the RMF qualitatively.

4   Summary and Remarks

In summary we have investigated the density dependence of the bag constant of nucleons, the nucleon radius and the total energy of the bag as well as the quark condensate in nuclear matter in the global color symmetry model, an effective field theory model of QCD. A maximal density of nuclear matter, which is larger than 12 times the normal nucleon density, for the existence of the bag of quarks is obtained. The calculated results indicate that the bag constant, the total energy of the bag and the quark condensate decreases with the increasing of the nuclear matter density before the maximal density is reached. Meanwhile the size of nucleons swells. As the maximal density is reached, a phase transition from nucleons to quark-gluons takes place and the chiral symmetry is restored. Furthermore, the presently obtained changing features agree with those obtained in QMC

and RMF quite well. In this sense, it provides a clue of the QCD foundation to the QMC and RMF with a simple effective field model of QCD.

In the present calculation, the $g^2 D(p-q)$ is taken to be proportional to a $\delta-$function. However, the detailed effects of the running coupling constant, the gluon propagator $D(p-q)$ and the other degrees of freedom on the changing feature have not yet been included. Especially, since the meson fields were taken to be $\sigma = 0$ and $\pi = 0$ in the bag with respect to those of the vacuum configuration $\sigma = 1$, $\pi = 0$, the self-consistent interaction and adjustment between the quarks and the meson fields have not yet been taken into account. Meanwhile, the relation between the chemical potential and the nuclear matter density was handled with a simple correspondence in statistical mechanics. It means that the present calculation is an approximation of the scheme. The obtained results are thus the preliminary ones. In principle, the quark energy (and field), the meson fields and the nuclear matter density can be determined by solving the set of differential-integral equations established from the action(Eq.(1)) of the system consistently. Such a sophisticated investigation is under progress.

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